REVIEW OF USBR/USGS SEDIMENT-TRANSPORT AND BEACH-EROSION REPORTS--
GLEN CANYON ENVIRONMENTAL STUDIES

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INTRODUCTION

General Statement

This report is a second statement for an ongoing analysis of studies being conducted by the U.S. Bureau of Reclamation (USBR) and U.S. Geological Survey (USGS). The USBR/USGS studies were undertaken to describe the characteristics of the sediment transport and beach erosion for the Colorado River between Glen Canyon Dam and Lake Mead. The sediment-transport and beach-erosion investigations are part of a comprehensive four-year (1983-1986) Grand Canyon Environmental Study (GCES) designed to examine the impacts of the existing operations of the Glen Canyon Dam and to identify possible feasible alternatives to the present operating criteria. Finding meaningful answers to questions pertinent to changes in selected alluvial deposits, called beaches, that result because of regulation of water is a main objective of GCES. The beaches, composed primarily of alluvial sediments of sand sizes, are of concern because they are camp sites for tourist rafting or hiking in the canyon. In addition, the alluvial deposits support riparian vegetation and wildlife which represents natural resources of the Grand Canyon.

The primary purpose of the ongoing analysis is to keep the U.S. National Park Service (NPS) informed of the progress, merits and limitations of the USBR/USGS sediment transport and beach erosion studies. Close examinations of all aspects of the

USBR/USGS study--the problem, the objectives, field procedures (network design, data-collection program), and office procedures (analytical methods and modeling effort)--are necessary for the ongoing analysis.

Basically, the first progress report (Burkham, written comm, 1984) presented:

1. General descriptions of the characteristics--general physiography, hydrological setting, and pre-dam river--of the Colorado River in the Grand Canyon.

2. General discussions of the hydraulic and physiographic characteristics of the problem encompassed by the USBR/USGS study.

3. Brief outlines of the objective, scope, and approach for specific USBR/USGS studies in progress in August 1984.

4. Brief details of the USBR/USGS hydraulic model, sediment-transport model, surveys of camping beaches, channel-bottom surveys, photo surveys, and delta-sediment provenance surveys.

5. Discussions regarding the application, limitation and uncertainty of approach for each of USBR/USGS studies, and

6. Conclusions and recommendations.

Tentative general conclusions outlined in the first progress report (Burkham, written comm., 1984) basically are as follows:

1. General statements about the source and disposition of the sediment being moved, and of changes in the character of sediment on the river bed can be made when the sediment-transport model become operational and analyses are made. However, predictions of the magnitude of "on site" changes and of long-range effects for the total channel that are based solely on outputs from the sediment-transport model should be in suspect because of the many uncertainties pertinent

to mathematical simulation, to the data used, to model calibration and to model application.

2. Reliable and direct answers to the question, "How is the present normal operation of the Glen Canyon Dam effecting changes in the camping beaches?" and to the question, "How long will the beaches be usable for recreation?" will not be obtained as a result of studies that were being pursued in August 1984.

3. In addition to their worth for the present (1983-84) program, results from the USBR/USGS sediment transport and beach-erosion studies will have value for the planning of subsequent studies.

Conclusions and recommendations contained in the first progress report (Burkham, written comm., 1984) were considered in the design of four studies started after August 1984. Investigations started after August 1984 were the USGS bar-stability, tributary-sediment, and rapid studies; and the NPS hydraulic-trend analysis.

Purpose, Scope and General Approach

The present (January, 1986) statement presents reviews and discussions related to draft reports that describe results of the USBR/USGS sediment-transport and beach erosion studies. Reports that were reviewed are as followed:

1. Sonar Patterns of the Colorado River Bed in the Grand Canyon by Richard P. Wilson.

2. Sediment Data Collection and Analysis for Five Stations on the Colorado River from Lees Ferry to Diamond Creek by Ernest L. Pemberton.

3. Sediment Transport and River Simulation Model by Tim J. Randle and Curtis J. Orvis.

4. Results and Analysis of STARS Modeling Effort of the Colorado River in the Grand Canyon by Tim J. Randle and Ernest L. Pemberton.

5. Unsteady Flow Modeling of the Releases from Glen Canyon Dam at Selected Locations in Grand Canyon by Jerold F. Lazenby.

6. Debris Flows from Tributaries of the Colorado River in the Grand Canyon National Park by Robert H. Webb, Patrick T. Pringly, and Glen R. Rink.

7. The Rapids and Waves of the Colorado River, Grand Canyon by Susan W. Kieffer.

8. Aggradation and Degradation of Alluvial Fan Deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona by Jack C. Schmidt and Julia B. Graf.

9. Topographic Surveys of Selected Sandy Beaches along the Colorado River in the Grand Canyon National Park by Ron Ferrari.

A brief synopsis and analysis is given for each report. The synopsis highlights objectives and study procedures and lists the products of the study.

The analysis considers: (1) Whether the report meets the needs of the NPS, (2) to what level the needs of the NPS are met, and (3) what long-term trends relevant to NPS interests does the study suggest. Basically, the needs of the NPS will be met when reliable and direct answers are obtained for the questions "How is the normal operation of the Glen Canyon Dam effecting change in the camping beaches?" and, "How long will the Beaches be usable for recreation?". The answers to these questions are obtainable only after a sound understanding of the dynamics of erosion, transport and deposition of sediment--clay to boulder sizes--for all components--alluvial deposits, main channel, rapids, eddies--of the river system is developed and this understanding is translated, in some way, to a capability to predict. Each of the different reports describes the results of a study that had as its goal the attainment of information about one or more components of the river system. For each report, therefore, the analysis includes a comparison of the information obtained against that which, in the opinion of the reviewer, should be obtained in order to improve the overall ability to predict--or answer the two questions presented above.

Positive aspects of the study, areas of concern and recommendations for follow-up studies beyond the life of the present (1983-86) USBR/USGS program are highlighted in the discussion sections. A listing of possible procedures available for the development of a capability to adequately predict are also included in the discussion section.

REVIEW OF REPORTS

Sonar Patterns of the Colorado River Bed in the Grand Canyon by Richard P. Wilson

Synopsis--The results of a study with a goal (USGS Memorandum dated October 21, 1983) "to quantitatively describe the profile and geometry of the river, the lithology of the material underlying the channel, and the volume or erodible sediment available to the river" are presented in the subject paper. The USGS researcher used distinctive patterns on side-scan sonar and depth-finder charts to delineate parts of the riverbed that had (1) a smooth bottom, (2) sediment waves, and (3) boulder and bedrock outcrops. He used aerial photographs, maps and water-surface profiles produced by Birdseye (1923), and bed-material samples in the delineation of the three types of riverbed surfaces. As described by the researcher, a smooth bottom is formed by sand and gravel in areas of low-velocity currents, by gravel and cobbles near riffles, rapids, or downstream sides of scour holes, and by sand near the banks. The sand waves, in areas of immediate velocities characteristically downstream from scour holes, are composed mainly of median to very coarse sand, fine gravel, and a few medium to large pebbles. Boulders and bedrock outcrops occur at riffles, rapids, upstream sides of scour holes, and along much of the banks.

The researcher used depth-finder charts, aerial photographs, and maps and water-surface profiles produced by Birdseye (1923) to quantitatively describe the geometry of the river in the Grand Canyon.

A set of 189 sonar-pattern maps are the major product of the study. About 75 percent of the 225 miles of river from Lee's Ferry to Diamond Creek is covered by the maps. About 25 percent of the of river was described as gaps in the coverage. The gaps resulted because of poor or no sonar image in rapids or places where the flow is highly turbulent, and because the sonar fish was removed from the water through major rapids.

Cross-sectional depths at 224 locations along the river and a depth profile for the thalweg of the river are also products of the study. The cross-sectional depths basically were taken in pools between rapids and or riffles.

Analysis--The study, if completely successful, would have provided three interrelated types of information for the USBR/USGS program, and for the NPS. It would have provided: (1) General descriptions of the geometry and lithology of the river that were not available prior to the 1983-86 study, (2) base-line data that can be used in future studies, and (3) sonar-map and water-depth data that are part of the input needed for the sediment-transport model. The study was partially successful, especially for types of information 1 and 2. The descriptions of the geometry and lithology of the riverbed are adequate to convey a message to the reader, (1) that the Colorado River in the Grand Canyon is unique among most major rivers in the United States; and (2) time-honored empirical approaches used to discuss and resolve sediment-related problems in other rivers should be used with caution in applications to the sediment-related problems in the Grand Canyon.

The study had only marginal success in providing type-3 information. Data representing river-channel geometry (locations, distances and elevations) and distribution (locations, areal extent, sediment sizes, and volume) of readily transportable sediments are the inputs required by the sediment-transport model. For reasons presented in the first progress statement (Burkham, written comm., 1984) the channel-geometry data are at the "brink" of not being adequate. The transportable-sediment data also contain major flaws as follows:

1. The data may contain relatively large errors in location and areal extent;

2. distribution of sediment sizes in the range from cobbles to sand is not described except in a general way;

3. the depth of transportable sediment along the bed of the river is not defined, and

4. flaws 1, 2, and 3 contribute to uncertainties in outputs from the sediment-transport model.

A resurvey of the thalweg of the river after known large inflows of sediment from tributary streams, particularly Little Colorado and Paria Rivers may prove beneficial in providing information about storage capacity for readily transportable sediments in pools in the river. The sonar and depth-finder surveys in 1984 were made in a period when the rivers pools probably were largely depleted of sand-size sediments (Burkham, written comm., 1986). Depletion of sediments in the pools occur during large floods in the Colorado River, such as the one that occurred in June 1983. The resurvey should provide information about the amount of sediment in storage during a full-pool regime--which probably exists after large sediment inflows from tributary streams. The differences in storage indicated by the results of the two surveys--the one in 1984 and the one to be made after a large sediment inflow--will give information about the storage capacity for readily transportable sediments in pools in the Canyon.

Sediment Data Collection and Analysis for Five Stations on the Colorado River from Lees Ferry to Diamond Creek
by Ernest L. Pemberton

Synopsis--The results of an investigation with goals of obtaining data needed for sediment transport studies are presented in the subject paper. According to the USBR researcher, the sediment transport studies were required in order to "evaluate the short and long term impacts of sediment movement on recreation, fisheries, vegetation, and beach erosion of the Colorado River through the Grand Canyon". The design of the data-sampling program and the analysis of data mainly were made to accommodate the needs of the sediment-transport model. The five sediment stations where data were obtained are at Lees Ferry, above Little Colorado River, near Grand Canyon, above National Canyon, and above Diamond Creek.

The products of the study for each of the stations are: (1) Records of discharge of water and sand-size sediments for two periods, and (2) equations relating the discharge of sand-size sediments to the discharge of water. The two periods of records are from June 30, 1983 to December 13, 1983, and from December 1, 1985 to February 2, 1986. The procedure for obtaining the products for each of the sediment sampling sites involves steps as follows:

1. Suspended-sediment samples were obtained periodically at several verticals in a cross section of the river. The samples were used to obtain data representing size distribution and concentration for suspended sediment. Step 1 involved laboratory and office analyses.

2. Bed-material samples were obtained periodically at the section. The samples were used to obtain data representing the distribution of the various sizes of sediment on the bed. Step 2 involved laboratory and office analyses.

3. The streamflow was measured periodically at the section to obtain data representing discharge and hydraulic parameters--mean velocity, cross-sectional area, stream width, mean depth of section applicable to the part of the cross-section where samples were taken, and water temperature.

4. The total-load discharge of sand-size sediments was computed. The modified Einstein method and five other sediment-transport equations, called predictive equations by the researcher, were used in the computations. Data sets obtained in step 1, 2, and 3 were used in the equations. Total-load discharge of sand includes the part of the total that moves near the bed, commonly called bed load. The same data used in the modified Einstein equation were used in the predictive equations except suspended-sediment data were not required.

5. For the modified Einstein method and for each predictive equation, the sand-size discharges obtained in step 4 were regressed against the discharge of water (step 3) and a "best-fit" equation relating the discharge of sand-size sediment to the discharge of water was developed for each sediment-sampling station.

6. For each of the "best-fit" equations, computed values of sand-size discharge were compared to values obtained using the modified Einstein method.

<u>Analysis</u>--The sediment-sampling program was required so that the discharge of sand-size sediment at the five selected sites could be determined for the two periods--June 30 to December 13, 1983, and October 1, 1985 to February 2, 1986. The sediment-discharge data were needed for:

1. General descriptions of the sediment--range in rates, volumes, distribution of sizes, change in sizes, etc.--being moved;

2. sediment-budget studies;

3. analytical, correlative and trend analyses;

4. sediment-transport studies, including modeling; and

5. base data for use in future studies.

The quality of the data obtained at the five sediment-sampling stations probably is adequate for the projected needs of the GCES. However, the user should be aware of the possible relatively large error in the data representing the total discharge of sand-size sediments. According to Burkham and Dawdy (1980), the overall standard error of estimate for the total-sediment discharge of all sizes of sediments--from clay through coarse gravel--determined by using the modified Einstein method is about 20 percent but may range from 25 percent for the discharge of fine sand to 135 percent for the discharge of coarse sand. Furthermore, if the modified Einstein method is used, the fine-sand discharges may be biased on the low side by as much as 15 percent and the coarse sand may be biased on the high side by as much as 20 percent.

The user of the sediment data described in the subject report should be aware of three other factors:

1. The Colorado River in the Grand Canyon, after the construction of Glen Canyon Dam, is primarily a supply-limited reach--the river could transport more sediment if it was readily available;

2. much of the sediment data described in the subject paper are for a period soon after the occurrence of a large flood and, therefore, the sediment data probably do not represent an average condition; thus the "best-fit" equations do not represent average conditions; and

3. beaches are composed primarily of sand in the range of sizes from .0625 to 0.50 mm (Smythe and Graf, written comm., 1986); the best-fit equations are for sizes in the range from 0.0625 to 2.0 mm.

The reviewer suggests that the standard error of estimate should be used as the measure of uncertainty. The researcher presented numbers that suggest that the coefficient of correlation for the best-fit equations range from 0.566 to .995 which suggest good agreement between values estimated using the best-fit equations and values obtained using the modified Einstein method. This apparent good agreement, however, is misleading. The relatively high coefficients of correlation (given in his table 10) result because the discharge of water is inherent in the <u>sediment-discharge</u> data. Thus in his analysis of correlation, water discharge is regressed against water discharge. Of the correlation coefficients given in table 10, roughly 0.70 is the part that is inherent because water discharge appears in both parameters--sediment discharge and water discharge.

The researcher stated that the same regression equation could be used at the sites near Grand Canyon, above National Canyon and above Diamond Creek. By making this statement, he apparently is implying, for the study periods in 1983 and 1985-

86, that only a small amount, if any, sediment is being eroded or deposited in the Colorado River from the sampling site near Grand Canyon to the one above Diamond Creek. This implication is suggested because, as can be shown by an application of the unsteady-flow model (Lazenby, written comm., 1986), only small differences in flow-wave magnitudes occur as a flow event moves downstream from the sediment-sampling site near Grand Canyon to the one above Diamond Creek.

Sediment Transport and River Simulation Model

by Curtis J. Orvis and Timothy J. Randle

Synopsis--The subject report, according to the authors, "describes the development and application of the STARS model to the sediment studies in the Grand Canyon". The researchers, in the development of STARS, used the basic concepts of a model formulated by Melinas (written comm., 1983). Basically the STARS--an acronym for sediment transport and river simulation--model is composed of two parts: The hydraulic portion and the sediment portion. These portions (or parts) are interconnected in the model with the basic assumption that the mean motion of the sediment particles is dictated by the motion of the water flow. At a given time step the hydraulic conditions prevailing at each cross section such as velocity, energy slope, flow depth and area are computed first by the hydraulics portion. These variables are then used to compute the sediment motion and new channel geometrics, which will be used at the next time step.

The data needed to execute the hydraulic portion of the

STARS model, according to the researchers, are discharge and geometric data to define the channel shape. The geometric data include cross-sectional profiles, channel-reach lengths between sections and roughness coefficients. In order to run the sediment portions in conjunction with the hydraulic portion, additional sediment data are required. According to the researchers

> "Basic input include representative sediment size gradations of the streambed material at each cross section... An incoming sediment load hydrograph or sediment-discharge rating-curve, corresponding to water discharge hydrograph, is required along with water temperature hydrograph to provide the upstream boundary conditions. A sediment transport method or algorithm must be selected which best fits the river conditions or available data in the study reach. Limits on the depth of degradation can be supplied by the user for the case where there is a known grade control or bedrock elevation below the streambed."

The STARS model, according to the researchers, "...is one-dimensional, meaning no attempt is made to simulate secondary currents in the hydraulic calculations and to compute sediment transport between streamtubes."

The researchers, in an effort to demonstrate application, used the STARS model to simulate scour and fill regimes in the East Fork River near Boulder, Wyoming and in the Colorado River between Glen Canyon Dam and Lees Ferry, Arizona. Sensitivity analyses of the model also were made, according to the researchers, "to determine the relative importance of the STARS model input data in prediction of the sediment transport".

The product of the study is the subject narrative, which include descriptions of results of the verification and sensitivity analyses.

<u>Analysis</u>--A sediment-transport model would be useful as a "tool" to be used to help resolve the main sediment problem encompassed by the GCES. Impacts of water and sediment regulation on selected alluvial deposits--deposits that are used for camping and that support vegetation--represent the main problem to be resolved. A model would be particularly useful if it had the capacity to simulate:

1. Water and sediment movement in the main channel upstream and downstream from rapids;

2. adjustments in the areal extent and elevations of rapids caused by external stresses induced by floods, debris flows, etc.;

3. the movement of water and sediment from the main channel to eddies, and from the eddies to the main channel;

4. the movement of water and sediment in secondary flow and eddies, and

5. adjustments in the areal extent and elevation of the alluvial deposits caused by external stresses induced by man's use of beaches; natural phenomena such as wind, rain, local run-off, floods and debris flows; and regulation of flow.

The subject model does not have the utility for the simulations described above--nor does any other model.

As presented in the first progress report (Burkham, written comm., 1984), the reviewer postulated "General statements about the source and disposition of sediment (sand sizes) being moved, and of changes in the character of the sediment on the bed can be made when the model described in this report becomes operational and analyses are made. However, predictions of the magnitude of 'on site' changes and of long-range effects for the total channel that are based directly on outputs from the sediment-transport model should be in suspect because of the many uncertainties pertinent to mathematical simulation, to the data used, to model calibration and model application". Basically, the postulation as written represents the reviewer's current (Jan. 1987) general conclusion. However, the postulation should have an asterisk and a footnote to make it current. The footnote statements are:

1. Descriptions pertinent to the general movement of sediment in the main channel can be obtained from the results of other studies (see footnote 3).

2. The descriptions from the other studies should be as reliable as those generated by the model and probably would require less effort to obtain.

3. A GCES report by the reviewer (Burkham, written comm., 1984) contains much information about the general movement of sand-and-gravel-size sediments in the Colorado River in the Grand Canyon. Other analytical and budgetary studies perhaps would be even more fruitful.

4. A comparison between results obtained from the model with results from the other studies perhaps would strengthen descriptions of the general movement of sediment in the main channel.

The researchers applied great effort to demonstrate the application, limits and uncertainty of use for the STARS model. They should be congratulated for this. However, for the application of the model to the data for the East Fork River, the researchers could strengthen their report if they would relate the RMS (0.17 meters) to a number representing the mean of changes in the thalweg at the different cross sections. For the application of the model to the data for the Colorado River, the researcher should consider developing a table that shows how great the overprediction is for the different lengths of channel in the upper portion of the reach and how much the underpredition is for the different lengths of channel in the lower portion of the study reach.

The use of the sediment data for 1959 to 1965 to verify the sediment-transport model may lead to misleading conclusions. In 1959, the Colorado River in the reach from Glen Canyon to Lees Ferry primarily represented a reach of unlimited supply of sand-size sediment when the water discharge was in the range from 3,000 to 31,000 cfs, the present release-pattern of discharges. In 1959, the rate of sediment discharge primarily depended on the hydraulic conditions prevailing in the reach. After about 1965, the Colorado River in the reach from Glen Canyon to Lees Ferry represents a supply-limited reach--the discharge of sand-size sediment depends on supply rather than hydraulics. Presently (1987), much of the Colorado River is supply limited.

Results and Analysis of STARS Modeling Effort of the Colorado River in the Grand Canyon by Timothy J. Randle and Ernest L. Pemberton

Synopsis--The STARS model, according to the researchers, "was used to determine the relative impacts on streambed erosion of the Colorado River, in the Grand Canyon, caused by various flow releases from the Glen Canyon Dam...Use of the STARS model...provides a predicted sand load at any beach within the Grand Canyon for any discharge. By routing different operation scenarios of the Glen Canyon Powerplant, comparisons of sediment transport are possible. This comparison of sand loads in the river under different operating patterns provides a means to evaluate the relative impacts of stream bed erosion."

The report describes, among other things, the results of 3 different applications of the model. The applications were made to simulate:

1. Hydraulic and geometric properties--water surface profiles, streamflow velocities, widths, depths, and area--at 708 cross-sections for a range in streamflow from 5,000 to 90,000 ft^3/s in the 225-mile reach of the Colorado River from Lees Ferry to Diamond Creek;

2. the sediment transport in two reaches--from the sediment-sampling station at Lees Ferry to the one above Little Colorado River and from the sediment-sampling station above Little Colorado River to the one near Grand Canyon--for two periods--June 1 through December 15, 1983 and October 1 to October 14, 1985; and

3. scour and fill in two reaches--from Lees Ferry to a site above Little Colorado River and from above Little Colorado River to a site near Grand Canyon--for two flow alternatives (representing potential operation scenarios of the power plant at Glen Canyon Dam).

Application 1 primarily was made to generate hydraulic and geometric data for applications 2 and 3. Input data for application 1 were:

1. 199 sets of cross-sectional data supplied by Wilson (written comm., 1986);

2. 509 sets of cross-sectional data interpolated from information:
   (a) supplied by Wilson (written comm., 1986);
   (b) scaled from aerial photographs;
   (c) water surface profiles developed by Birdeye (1923):
   (d) water surface elevations supplied by USGS; others were obtained during USBR surveys (Ferrari, written comm., 1986);

3. an assumed value of 0.035 representing the manning's roughness coefficient "n"; and

4. assumed correction factors needed to obtain agreement between the Birdeye profile and 1984 water surface elevations.

Application 1 utilized the step-backwater feature of the model in which the discharge is assumed constant and the channel-boundary is assumed to be rigid.

Application 2, according to the researchers, primarily was made as a check on the validity of using the model in the Grand Canyon. Input data for application 2 were:

1. Cross sectional data--elevations, distances, and roughness--obtained in application 1;

2. bed-sediment sizes and distribution interpolated mainly from information supplied by Wilson (written comm., 1986), and from bed-material samples obtained at sediment-sampling station's (Pemberton, written comm., 1986);

3. discharges obtained at USGS streamflow stations in the Colorado River and tributary streams; and

4. water-discharge-to-sediment discharge relationships for sediment-sampling stations on the Colorado River (Pemberton, written

comm., 1986) and tributary stream (described in the subject report).

Application 2 utilized the sediment-transport features of the model in which the discharge and elevation of the river bed can vary.

Application 3, according to the researcher was made for prediction purposes. Input data for application 3 were the same as those for application 2 except that "the sand and gravel bed material were both assumed to rest on bed rock or a non-erodible material and have an initial thickness of 20 feet."

Analysis--The reviewers pessimistic opinions about the merits of the subject model is well documented (Burkham, written comm., 1984). Unfortunately, the results of the application of the subject model to the sediment-transport and erosion problem in the Grand Canyon did not change this opinion. Actually, several of the assumptions, simplifications, and adjustment that were made in the verification (application 1 and 2) and flow--alternative runs of the model are causes for increasing the feeling of doubt about the reliability of results. The discussions that are given in the following three paragraph are presented as examples to exemplify the reasons for the increase in doubt.

For the first application (application 1) of the model, if the adjustment value of 5 feet contained a significant error, a high level of uncertainty in results of model application could be generated. The 5-foot adjustment in elevation was necessary to obtain agreement between model-produced profiles and those determined by Birdseye (1923). If converted to discharge at the USGS gaging near Grand Canyon, the 5-foot adjustment would be approximately equivalent to about 70,000 ft^3/s (Burkham, written comm., 1986); if converted to total-sediment discharge the 5-foot adjustment would be approximately equivalent to about 170,000 ton/day (Pemberton, written comm., 1986).

The initial run in the second application of the STARS model, using the 1983 flow hydrograph, gave total-sediment discharges for the site above Little Colorado River that were only about 28 percent of the measured values. With adjustments--apparently arbitrarily assigned-- to the bed-material distributions, a second run gave total-sediment discharges that were about 61 percent of the measured values. The researchers stated "from the two trial computations, it appears that either by making more of the bed material SW (sand waves) or by decreasing the size graduation to finer sand size sediments, an increase is sand load of up to about 5,700,000 tons or 2700 acre-feet would be possible. The additional time to make the trial and error runs to reproduce the June 1983 bed material size gradation was not considered." The researchers seem to imply that the size distribution of bed material was the only possible reason for the initial poor agreement between computed and measured total-sand discharge. The researchers apparently did not consider the fact that the model does not account for the erosion of alluvial deposits--beaches--along the water edge as being a likely reason for the poor results. Several other possible reasons exist for the poor agreement between computed and measured values (Burkham, written comm., 1984).

The researchers stated that "the sand and gravel bed materials were assumed to rest on bed rock or a non-erodible material and have an initial thickness of 20 feet". There is no apparent basis for this assumption, which was made in the third application of the model.

Total sediment supply at the main stem upstream boundary for each of two reaches, in the third application of the model, was computed as a function of the discharge hydrograph using the modified Einstein water discharge-to-sediment discharge rating curve developed by Pemberton (written comm., 1986). First, doubt or uncertainty is introduced because a strong argument can be presented that the Pemberton sediment rating curve represents a condition that prevails only after a large flood and thus is not representative of an average condition. Second, the discharge hydrograph was obtained from an application of the SSARR unsteady flow model (Lazenby, written comm., 1986) and the discharges generated by an application of the SSARR model may contain relative large errors. The errors in the discharge values are magnified by a factor of about 4 when the computed discharges are applied to Pemberton's equations.

Unsteady Flow Modeling of the Release from Glen Canyon Dam at Selected Locations in Grand Canyon by Jerold Lazenby

Synopsis--The purpose of the USBR study was "the development of an unsteady flow routing model for the Colorado River below

Glen Canyon Dam". The model is to be used in resolving problems pertinent to the timing and attenuation of release flow as the flow wave moves through the Canyon. Also, outputs from the subject model is to be used as inputs to the sediment-transport model (Pemberton and Randle, written comm., 1986). Basically, the researcher approach involved 3 steps as follows: (1) A model was selected; (2) the model was calibrated for specific sites in the Colorado River in the Grand Canyon; and (3) the advantages and limitations of the model were determined. The researcher selected a simplified mathematical model called, SSARR, for calibration. The model SSARR, an acronym for Streamflow Synthesis and Reservoir Regulation, has been widely used by state and federal agencies since its development prior to 1956.

The calibration of the subject model primarily involved the varying of three parameters (number of routing phases, time of storage per phase, and a dimensionless coefficient) until the timing and rates of computed flow hydrograph (output from model) agree as closely as possible with that of a measured flow hydrograph for a reach (or reaches) of interest. The researcher's calibration of the model was based on 1985-86 flows measured at six locations on the Colorado River as follows:

1. Glen Canyon Dam (mile -16)
2. Lees Ferry (mile 0)
3. Above Little Colorado Dam (mile 16)
4. Near Grand Canyon (City) (mile 87)
5. Above National Canyon (mile 167)
6. Above Diamond Creek (mile 226)

According to the researcher "The model as it is now configured will compute flows directly only at the stations used in its calibrations". The researcher presents a procedure for estimating flow rates at sites other than those used in the calibration.

Analysis--A relatively wide range of hydraulic models exist for routing of open-channel flow. Basically, the range is from a model requiring a large input of data for calibration to one that requires only a small input of data. The ones that requires the large input of data usually gives the most accurate results because the factors that affect the timing and attenuation of a flow pulse as it moves downstream are properly considered. However, because of ease of application the data-intensive models are not preferred for those studies where highly accurate outputs (from the model) are not required.

The researcher (for the subject paper) used a model that required a very limited amount of data. Obviously, some factors pertinent to the timing and attenuation of the flow pulse are not considered except in a general or average way. He listed disadvantages of the model as:

1. The model assumes a constant travel time between stations regardless of the magnitude of the flow pulse. Travel time normally varies inversely with discharge.

2. Errors tend to accumulate as computations proceed downstream because the output from a reach becomes the input at the next.

3. Flow discharges can only be computed directly at the stations used in the original calibration.

The researcher states that the model as now configured has several biases: It tends to underpredict peak flows by as much as 700 to 1100 ft^3/s on the average and overpredicts flow at the trough by several hundred cubic feet per second. It tends to predict the arrival of a peak discharge about 1 hour later than it should and the arrival of the trough about one hour sooner than it should. The researcher states that "If the exact magnitude and times of the predicted peak and troughs (of a flow event) are essential to the user of this model, they are advised to make these adjustment (to correct for bias in discharge and in travel time) to the computed data results."

The reviewer suggests another major disadvantage of the subject model exists. <u>It does not properly account for changes in travel time and in attenuation of peak discharge that result because of scour and fill in pools.</u> The reviewer found (Burkham, written comm., 1986) that, on an average, for a discharge of 20,000 ft^3/s at the USGS gaging station at Lees Ferry, the mean cross-sectional velocity was 10.2 ft^3/s when the pool at the gage was full of readily transportable sediment and 2.3 ft/s when it was depleted of the sediment. The reviewer found similar differences in velocity at the gage near Grand Canyon. Travel times varies inversely and attenuation of flow rates varies directly with velocity. A significant part of the total length of the Colorado River in the Grand Canyon consists of pools in which readily transportable sediment can be stored.

The subject model may have satisfactory-to-marginal utility to estimate flow rates at different times at selected camping beaches, at biological-sampling sites, and at sites where accidents have occurred. The subject model, because of errors, probably would have no utility for generating input data for an unsteady sediment transport model.

Debris Flows from Tributaries of the Colorado River in Grand Canyon National Park, Arizona by Robert H. Webb, Patrick T. Pringle, and Glen R. Ruck

Synopsis--The results of a study with the purpose "to document the extent of debris flows in Grand Canyon National Park and the occurrence and magnitude of debris flows in three Colorado River tributaries" are presented in the subject paper. The USGS researchers used data obtained during detailed-level field surveys to approximate debris-flow magnitude and frequency for three Colorado River tributaries. They used data obtained during reconnaissance-level surveys to document the areal extent of debris flow in 36 small drainages that are tributary to the Colorado River in the Grand Canyon.

Surveys of the areal extent of debris-flow deposits were the basis for evaluating the areal extent of debris flow in the 36 drainages. Debris flows are flowing water-based slurries of poorly sorted clay-to-boulder sized particles. Debris-flow deposits, according to the researchers, were recognized "on the basis of characteristic particle sorting, sedimentary structure, and inferred rheological properties". They state that "Debris-flow deposits are characterized by lack of sedimentary structure, poor sorting of particles, matrix-support of cobbles and boulders, and, in some cases, inverse fine-to-course grading."

The debris-flow magnitude and frequency for each of the three drainages--Lava-chuar, Monument and Crystal-- primarily were evaluated according to three tasks: (1) The number of debris-flow events in a time frame was determined, (2) the chronological order or dating of the debris-flow events were established, and (3) The magnitudes of the flow events were evaluated. Basically, the procedures used for task 1 and 2 involved the study of stratigraphy and sedimentology in the drainage for documentation purposes; radiocarbon analysis for dating of organic samples taken from a debris-flow deposits; and tree-ring analysis for dating the scarring of trees along the path of a debris flow. Historical photographs, aerial photographs and damages to historical structures provided additional sources of information for dating debris-flow events.

The magnitudes of flow (peak discharge rates) in the three drainages were determined using three simplified hydraulic equations, which are commonly used in similar studies. Data needed to use the equations were obtained during field surveys of the three drainages. During their investigation, the researchers relied heavily on information (data, conclusions, speculations) contained in a report by Cooley and others (1977).

Analysis--On the one hand, in comparing results to the stated purpose of the study, the subject study was very productive and complete. The subject report represents a good contribution to GCES and to the technical literature. The researchers presented excellent discussions of the debris-flow occurrences among tributary streams that were studied. They presented good descriptions of the distribution of sediment sizes among the different debris-flow deposits, and how debris flows affect (and/or effect) the formation of alluvial fans, rapid, riffles, hydraulics of flow, and formation of beaches. Their compilation and discussion of the technical literature was excellent.

On the other hand, in comparing the information contained in the subject report with that needed to develop reliable and direct answers to questions about the impact of regulation of flow on beaches, a conclusion is reached that the scope of the subject study was too limited. More information about the frequency of episodic events and about the input of sediment to the Colorado River is required.

In presenting a discussion about the need or importance of the subject study and of the accumulation of more information, it is convenient to present an argument contained in a memorandum from D. E. Burkham to Robert McNish dated December 27, 1985. The argument is:

> "Tributary streams not only supply large amounts of sand-size sediments but also most of the large gravels, cobbles and boulders that are found along the Colorado River in the Grand Canyon. Landslides that extends directly to the river supply some of these materials. Thus the tributary streams and landslide sites are the primary 'source area' for the 'base material' in tributary (alluvial) fans and in most of the rapid sections.
>
> The alluvial fan and rapids, to a large extent, control the hydraulic conditions in the vicinity of the fan and rapid. In turn the hydraulic conditions not only control the movement of sediment in the main channel but also control the locations of beaches and the movement of sand to and from the beaches. For a given location along the Colorado River, if the

character of a fan or rapid changes significantly then the hydraulic conditions undoubtedly would change also. Debris flow and landslides change (the character) of alluvial fans and rapids.

Major floods occurring simultaneously in several tributary streams could produce debris flows (and landslides) and deposition that could significantly change the hydraulic conditions of the Colorado River in many places. This probably has happened many times in the past--it occurred in a small way (at Crystal Rapids) in December, 1966 (Cooley, Alridge, and Euler, 1977)."

Obviously, the subject study was needed. The researchers stressed the importance of the study in the final paragraph of the subject paper. Keiffer, (written comm., 1986) also have stressed the importance of debris flows in influencing the formation and dynamics of rapids, riffles, beaches, channel hydraulic and sediment transport in the Colorado River in the Grand Canyon. The regulation of flow at Glen Canyon Dam changes the debris-flow and debris-deposits influences.

The types of information, about the frequency of episodic events and about the input of sediment from tributary streams, that are needed are relatively easy to visualize or to describe. However, the information is difficult to obtain. Basically, the required information relate to five questions:

1. What is the probability of an episodic debris-flow event occurring in at least 1 drainage in any one year or in several years (say 5 or more)?

2. What is the probability of episodic events occurring in several drainages (say 5 or more) in any one year or in several (5 or more) years?

3. How greatly does the debris-flow of a size that reaches the Colorado River periodically from at least one drainage influence the

formation and dynamic of rapids, riffles and beaches?

4. How greatly does the debris-flow of a size that reaches the Colorado River periodically from several drainages influence the formation and dynamics of rapids, riffles and beaches?

5. What is the annual volume of beach-building sediment--very fine to medium sand--from the ungaged tributaries? Is it significant compared to that from the gaged tributaries--Paria and Little Colorado Rivers? Is it a significant part of the total annual supply available for beach building?

The subject report gave partial answers to these questions.

The Rapids and Waves of the Colorado River, Grand Canyon, Arizona
by Susan Werner Kieffer

Synopsis--The objective of the USGS study, according to the researcher, was to obtain data on the configuration of the channel of the Colorado River in the vicinity of the rapids and on the hydraulics of the river in the rapids. The researcher used data obtained during two river trips to describe the Colorado River at and near twelve major rapids. The rapids are House Rock, 24.5 mile, Hance, Cremation, Bright Angel, Horn, Granite, Hermit, Crystal, Denbendorff, Lava, and 209-mile. The data obtained during the trips were: (a) time-lapse photography of the rapids as discharge was varied during fluctuation flow from about 7,000 cfs to about 20,000 cfs; (b) control-point surveys to provide data for construction of topographic maps by cartographic methods; (c) photographs of the trajectories of floats through the rapids for analysis of stream lines and velocity; (d) preliminary descriptions of the size distribution of large boulders lining the channel of the river. The researcher presented descriptions and discussions concerned with:

1. Common geomorphic and hydraulic features of the rapids;
2. locations of the rapids;
3. channel geometry and hydraulic structures;
4. rapids, pools, and scour holes;
5. a generalized hydraulic model for the rapids;
6. pools and backwater;
7. the tongue and oblique lateral waves;
8. the breaking waves;
9. large rock in the rapids;
10. erosion of large boulders and contouring of the channel;
11. rapids and rock gardens;
12. rapids and eddies;
13. the minor effects--river curvature.

The product of the study, according to the researcher, consists of the subject report; of a video cassette showing the major hydraulic features at ten of the twelve rapids that were studied; and of ten hydraulic maps of the rapids. The video cassette was not available for review.

Analysis--Along with the supply of sediment and the discharge of water, the rapid is probably the most important characteristic of the Colorado River pertinent to the formation and dynamics of beaches. Therefore, reliable and complete information about the formation, dynamics and influences of rapids is critical to the GCES studies. Basically, six general types of descriptions pertinent to the rapids are needed. The six interrelated types of descriptions are those concerned with:

1. Number, location and areal extent of rapids in the Grand Canyon; how and why the rapids are formed;

2. adjustments in the aerial extent and elevations of alluvial deposits at rapids caused by external stresses induced by floods, debris flows and other weathering agents;

3. ties and links between the formation and dynamics of rapids and the formation and dynamics of beaches; how much can the alluvial deposit at a rapid change without influencing significant changes in a beach;

4. ties or links between the formation and dynamics of rapids and the navigability of the river;

5. the magnitude and frequency of occurrence of those stresses--floods and debris flow--that would influence significant changes in the rapids during unregulated and regulated flows; and

6. the effects of regulation of flow on the debris deposits at rapid and on the influence of these effects on the beaches.

The descriptions in the subject report overlap into all the types listed above. The report gives excellent descriptions <u>on the configuration of the channel of the Colorado River in the vicinity of the rapids and on the hydraulics of the river in the rapids</u>, which is the stated purpose of the study. Type 1 and type 4 descriptions are excellent and basically are complete. However, in the opinion of the reviewer, types 2, 3, 5 and 6 will require more effort.

The reviewer believes that much of the discussion concerned with elementary hydraulics on pages 20-31 could be deleted or placed in an appendix without detracting from the report. Also, much of the discussion concerned with definitions of commonly used terms on pages 12, 13, 26 and 32 could justifiable be deleted or placed in an appendix.

Reasons for not reaching the goals outlined in the research proposal dated August 29, 1985 also should be discussed in the subject paper. Goals were outlined as follows:

1. Development of a classification for the origin of the rapids.

2. Creation of hydraulic maps showing
   a. bare-rock configuration
   b. waves at about 20,000 cfs
   c. waves at 50,000-70,000 cfs
   d. waves at 100,000 cfs

3. Measurement of velocity and depth, and the development of rating curves(?), for about 12 rapids.

4. Analyses of hydraulic and energy balances through about 12 rapids.

5. Verification of a proposed (?) hydraulic-geomorphic model.

6. Evaluation of the relative roles of chemical and physical agents in the modifications of large boulders.

Recent Aggradation and Degradation of Alluvial Fan Deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona
by Jack C. Schmidt and Julia B Graf

Synopsis--The researcher state that the purpose of the subject report "...is (1) to present a classification of alluvial sand deposits that serves as a framework for evaluation of change, (2) to illustrate the processes that influence sand deposit location and change and (3) to document patterns of change observed in the past 3 years and place these changes within the context of sand deposit change since completion of Glen Canyon Dam." The study involved the evaluation of existing data and the collection and evaluation of new data. Existing data consist mainly of aerial and ground photography; and topographic surveys of deposits that were begun in 1974. Data obtained from May 1984 to February 1986 include measurements of flow velocity, documentations of scour and fill of sand deposits, topographic and bathymethic surveys, observations of flow-circulation patterns, water-surface slope surveys, sedimentalogical analysis of some sand deposits, and replication of photographs. The study area extends from the gaging station at Lees Ferry to the gaging station near Diamond Creek. Data was collected in the vicinity of beaches at 41 sites. Bathymetric surveys, made at discharges between 15,000 and 25,000 ft^3/s, were limited to reaches where the raft could be safely maneuvered and instruments could receive signals. Topographic surveying was limited to areas of safe wading. The comparison of repeated topographic and bathymetic surveys of sand deposits was the primary means by which changes during the present study period, 1984-86, were determined. Photographic comparisons are the principal means of assessing changes during 1965-1984. Other methods used to interpret or document topographic changes or hydraulic conditions include scour chains's, sedimentologic descriptions, water surface slope surveys, and mapping of surface currents.

The product of the study are the subject narrative and 40 illustrations, mainly maps and graphs on which data and results of analysis are summarized.

<u>Analysis</u>--The subject report deals directly with the main problem to be resolved by the GCES. In order to resolve the main problem, a need exists to develop the capability to adequately predict: (1) What will happen to the beaches in the next 50-100 years if the regulation of flow does not change from its present pattern; and (2) what regulation pattern is preferred to enhance the continuous useability of the beaches. In order to adequately predict and to resolve the main problem, several types of information for beaches are needed. In general, the types relate to:

1. classification of the different types of alluvial deposits that are used for camping;

2. descriptions of each type;
   a. locations in reference to rapids or other main channel features; locations in reference to alluvial fans;
   b. the movement of water and sediment in the eddies;

4. descriptions concerned with changes in the beaches that occur when there is relatively high sediment discharge in the main channel; changes when main-stem sediment discharge is relatively low;

5. descriptions concerned with changes in a beach that result because of a large change in the areal extent and elevation of an upstream or downstream rapid;

6. descriptions concerned with the areal extent, elevation, and processes for changes in the beaches during;
   a. 1963-82;
   b. the high flows of 1983-84;
   c. the fluctuating flow in 1985-86.

The researcher gave excellent information of types 1 and 2, and fair to good information of types 3 and 6. However, they need to apply additional effort to obtain more information of types 4 and 5. Additional studies of processes involved at times when the sediment movement in the Colorado River is known to be relatively high--for instance when the Little Colorado River has a high discharge--may give meaningful results of type 4.

The subject report gives excellent descriptions of the features of the different typed of alluvial deposits in the Grand Canyon and of changes in the sand deposits in 1984-86. Their discussions of the different aspects of sedimentation also are good. However, the researchers apparently overlooked several opportunities to discuss the fluvial process. In the first paragraph on page 53, for example, they state that "Alluvial deposits within recirculating zones...are composed primarily of median to very fine sand". What is the significance of this statement? Why doesn't coarse sand and gravel appear in the deposit? How much of the sediment discharge at nearby gaging stations is in the range of median to very fine sand. In the second paragraph on page 70, they state "Separation deposits may be finer than reattachment deposits". Why? In the first paragraph on page 96, the researchers describe "a larger, deep recirculation zone" which indicates a difference because most recirculation zones are shallow. Why is it deep while others are shallow? On page 103, they state that "A substantial portion of this bar, therefore, degraded at least 4.5 ft between 1965 and

1973". Why did it degrade? Why didn't others degrade an equal amount? On page 116, they state "The recirculating zone at Eminence Break Camp at river mile 44.2 in very different in shape from that at Blacktail Rapid; it is also twice as long as it is wide". Why is this important? On page 118, the researchers state "Just below National Rapid at mile 166.6 the recirculation zone is similar in shape to that at Eminence Break Camp." Is this important?

Detailed discussions of the different anomalies contained in the report probably are not justified. However, brief statements concerned with why they occurred probably is worth the effort.

The report contains some apparent discrepancies in results and/or conclusions. For instance, on page 4 of the Executive Summary and on page 53 and 70 in the text, statements are given that say the separation deposit, reattachment deposit, and the bed of the recirculation zone are composed of median to fine sand. However in paragraph 3, on page 5 of the Executive Summary, the statement "<u>Exposure of armoring material at separation deposits restricted erosion</u> at some sites..." is given. An obvious question is "Where did the armoring material come from?" Is this another anomaly that should be discussed?

Some of the goals described in the study proposal dated December 27, 1986 apparently were not obtained. For instance, the goal of relating long-term changes in the beaches "to geomorphic variables measurable from photo or easily measured in the field" apparently was not reached. Also, the goal "to distinguish and quantify bar changes not attributable to mainstream river processes" was not obtained.

Topographic Surveys of Selected Sandy Beaches Along The Colorado River in the Grand Canyon National Park by Ron Ferrari

Synopsis--The purpose of the subject study, according to the researcher, was to establish a survey data base at several study sites for monitoring changes of the sandy beach areas along the Colorado River below Glen Canyon Dam. The survey of a beach basically required four steps:

1. Vertical and horizonal controls were established by monument;
2. Three or more range lines were established and surveyed--elevations and distances were determined;
3. topographic maps showing contours were developed; and
4. photographs showing as many features of the beaches as possible were taken.

The products of the investigation are a narrative summarizing the results of the study, survey data, written descriptions of the beaches and of locations of monuments, photographs, area maps showing location of beaches, and contour maps. Twenty-five beaches were surveyed.

Analysis--The study accomplished the stated objectives and these objectives basically agree with the needs. Repetitive surveys of the beaches should be continued until a definite trend of erosion, of aggradation, or of no change has been established. This probably will take 10 or more years. This data will be useful for ascertaining the magnitude and location of any beach-erosion problem and for prediction purposes.

DISCUSSIONS

Introduction

Primarily, the success of the sediment studies will be judged on the ability of the researchers to resolve questions pertinent to the camping beaches. Examples of questions that need to be resolved are "What will happen to the beaches in the next 50-100 years if the regulation of flow does not change from its present pattern?" and "What regulation pattern is preferred to enhance the continuous useability of the beaches?" The ability to correctly predict is a requirement adequately answering these questions.

In studies dealing with sediment-related problems, the capability to predict commonly is structured around one or more of the following interrelated factors or procedures:

1. Supply of sediment; mass-balance procedures;
2. forces, stresses and responses; deterministic processes; analytical and cause-and-effect analyses; modeling;
3. opportunity for change; probability and stochastic processes; empirical approaches;
4. historical records of changes; future changes related to past changes; trend analysis;
5. results of other studies; transfer of information; correlation analyses; and
6. experience and good judgement of the researchers.

The factors listed above are considered in the following discussions. For convenience, the discussions are grouped according to main channel, tributaries, rapids and beaches.

Main Channel

Based on the results of the GCES, a good description of the function of the main channel in the beach-erosion process can be presented. However, the reliability of answers to questions concerned with camping beaches probably would be improve if:

1. mass-balance procedures were utilized to develop drought-year, normal-year and (tributary) flood-year budgets of sediment for the total study reach and for selected sub-reaches;

2. analytical and trend analyses are made using the historical sediment records for the two gaging stations "Colorado River at Lees Ferry, Arizona" and Colorado River near Grand Canyon, Arizona";

3. the results from 2 were intergraded with results obtained by Burkham (written comm., 1986);

4. the probability of occurrence of large mainstream floods, such as the one in 1983, were determined;

5. thalweg of the Colorado River was resurveyed after a large inflow of sediment from Paria and Little Colorado Rivers; and

6. the thalweg profile obtained in 5 was compared to the one for 1984.

Additional runs of the sediment-transport model is not recommended.

Tributaries

The report by Webb and others (written comm. 1986) was very informative and represents an excellent contribution to the GCES and to the technical literature. In comparing results of the study to the stated objectives, the study was complete. However, more information about the frequency of episodic events and about inputs of sediment is needed. Basically, the required information related to five questions:

1. What is the probability of an episodic debris-flow event occurring in at least 1 drainage in any one year or in several years (5 or more)?

2. What is the probability of episodic events occurring in several drainages (say 5 or more) in any one year or in several (5 or more) years?

3. How greatly does the debris-flow that reaches the Colorado River periodically from at least one drainage influence the formation and dynamics of rapids, riffles and beaches?

4. How greatly does the debris-flow that reaches the Colorado River periodically from several drainages influence the formation and dynamics of rapids, riffles and beaches?

5. What is the annual supply of sand-size sediment from the ungaged tributaries.

The report by Webb and others (written comm., 1986) gave partial answers to these questions.

Rapids

Keiffer (written comm., 1986) presented excellent descriptions of the configuration of the channel of the Colorado River and of the hydraulics of open-channel flow in and in the vicinity of rapids. However, more cause-and-effect information is needed. The required information relates to:

1. adjustments in the areal extent and elevations of alluvial deposits at rapids

caused by external stresses such as floods and debris flows;

2. ties and links between the formation and dynamics of rapids and the formation and dynamics of beaches;

3. the magnitude and frequency (probability) of occurrence of those stresses--floods and debris flows--that would influence significant change in the rapids during regulated and unregulated flows; and

4. the effects of regulation of flow on the debris deposits at rapids and on the influence of these effects on the beaches.

Prediction capability pertinent to beaches would be improved if more analytical and cause-and-effects analyses were made in the four areas listed above.

Beaches

Schmidt and Graf (written comm., 1986) made good contributions to knowledge concerned with classifications and descriptions of alluvial deposits used for beaches. Their research mainly focused on changes in the beaches in 1965-86 and aggradation and degradation processes at the beaches in 1984-86. Additional effort is needed in order to obtain more information related to:

1. Descriptions of processes involved in the formation of each type of alluvial deposit which includes;
   a. the development of ties or links between discharge of water and sediment in the main channel and the discharge of water and sediment in eddies;
   b. the movement of water and sediment in the eddies;
   c. changes in the beaches that occur when there is relatively high

sediment discharge in the main channel;

2. descriptions concerned with changes in a beach that results because of a large change in the areal extent and elevation of an upstream or downstream rapid;

3. probability that the part of the beach that is utilized most, the upper part, is overtopped and/or destroyed by a major flood; and

4. beach changes not attributable to mainstream river processes.

Conclusions

Except for mass-balance and probability concepts, the GCES studies made reasonably good use of the different procedures commonly utilized to improve knowledge about a sediment-related problem. The information developed in the nine reports and in a report by the reviewer (Burkham, written comm., 1986) is sufficient to allow for: 1) a reasonable estimate of changes in the main channel, rapids and beaches since construction of Glen Canyon Dam; 2) good descriptions of fluvial processes for the main channel, rapids and beaches; and 3) reasonable speculations of what will happen to the beaches in the next 50-100 years and of what regulation pattern is preferred to enhance the continuous useability of the beaches. The reasonable speculations, however, will have to be conditioned with several "if" statements. For example, the prediction will be reasonable only if a series of main-stream major floods, if 100-year floods in the Paria and Little Colorado River, and if many episodic debris-flows in tributary streams do not occur. The additional studies described in the "Discussion" section, especially the mass-balance and the probability studies, are needed to improve on the capability to predict and to develop a better understanding of the magnitude and frequency of flood, and of episodic events.

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